



Feeling the Pulse of the Stratosphere: An Emerging Opportunity for Predicting Continental-Scale Cold Air Outbreaks One Month in Advance

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Sources of Prediction Skill

- **NWP:** initial value problem. Rossby waves and baroclinic system => chaotic nature => inherent predictability (1-2 weeks).
- **NWP + lower boundary forcing: “forced” problems** Internal variability often is as large as the forced anomalies, particularly in the absence of large SST anomalies (e.g., non ENSO years) and over the regions where prominent atmospheric internal modes are present at all time scale => **the forecasts of the “forced” anomalies are indecisive.**
- **New Source:** Global mass circulation => The extratropics is connected to the tropics via stratosphere: => A much longer time scale.

The Needs for Predicting Cold Air Outbreaks at a Long Lead Time

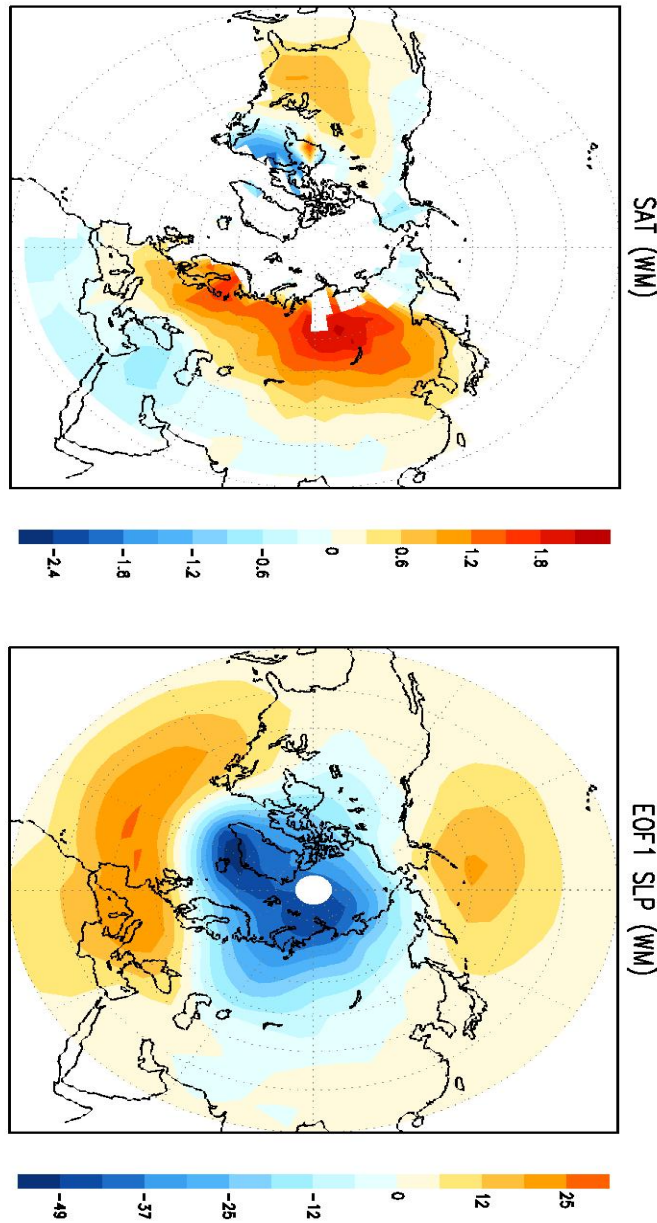
- Cold air outbreaks are frequently occurring extreme events with a large-impact area in winter seasons.
- Accompanied with cold air outbreaks are wintery storms (e.g., snow, frozen rain, high wind, icy/freezing).
- Forecasts of wintery storms at a long lead time help business and governments to prepare for potential threats to the society and business functioning (school/business closure, road/highway snow removal and deicing, flight cancellations, loss of agricultural products, etc.)

The minimum requirement to predict cold air outbreaks at a long lead time beyond the inherent 2-week limit of predictability for weather forecasts using the existing NWP model

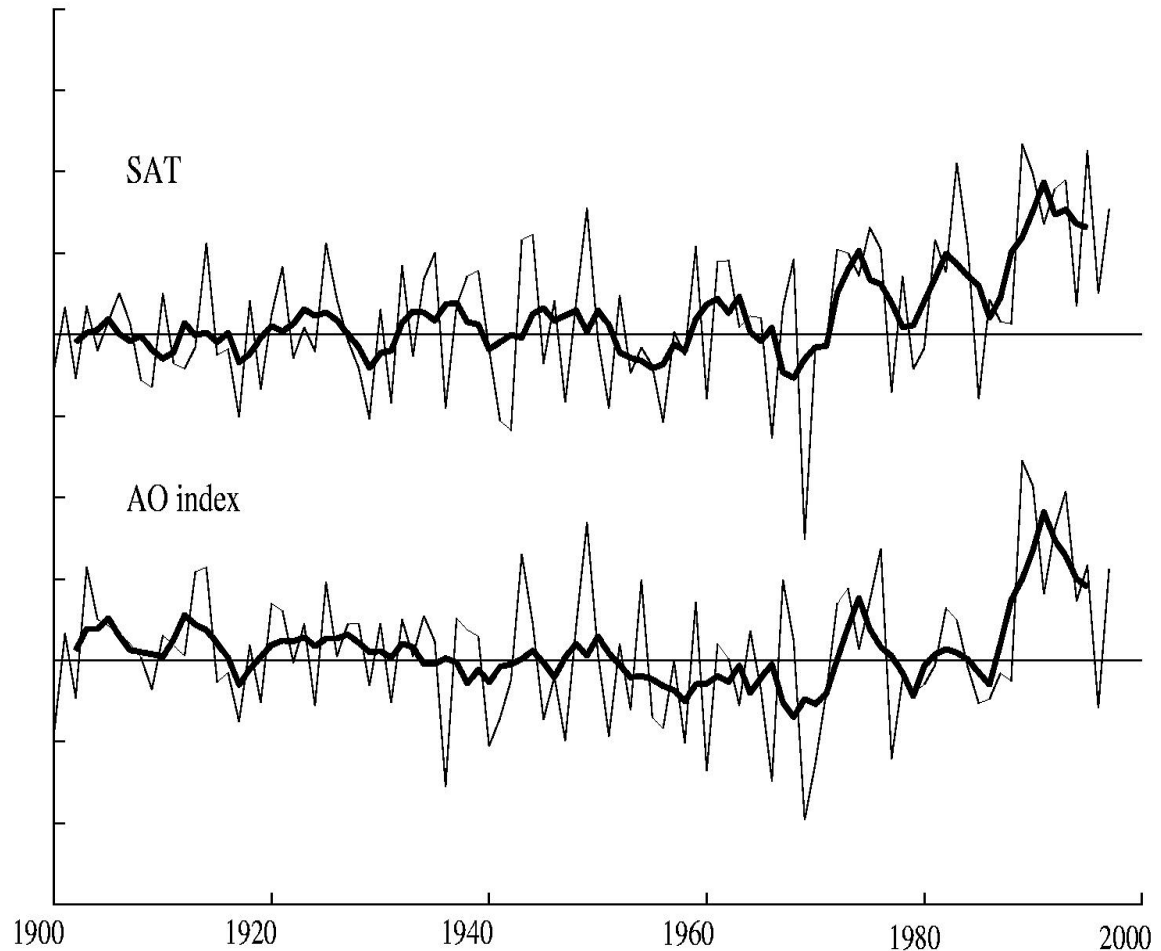
- Existence of robust diagnostic relations between some circulation indices and cold air outbreaks.
- The circulation indices that have robust diagnostic relationships with cold air outbreaks can be predicted by operational models at a long lead time with a reasonably good skill.

**Key circulation indices that have
good diagnostic relationships with
(monthly or seasonal) mean
temperature anomalies**

AO and Seasonal Mean Surface Air Temperature Anomalies



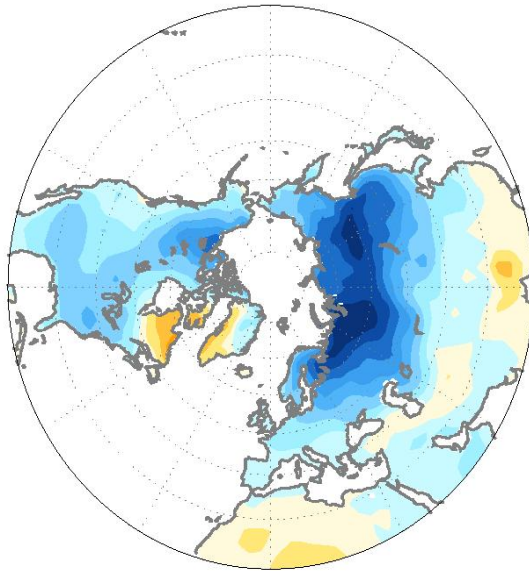
Seasonal Mean SAT



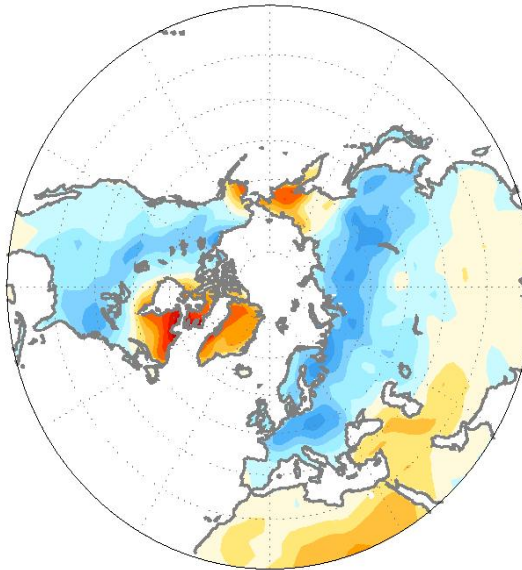
Thompson and Wallace (1998, GRL)

Stratospheric NAM and Winter Mean SAT anomalies

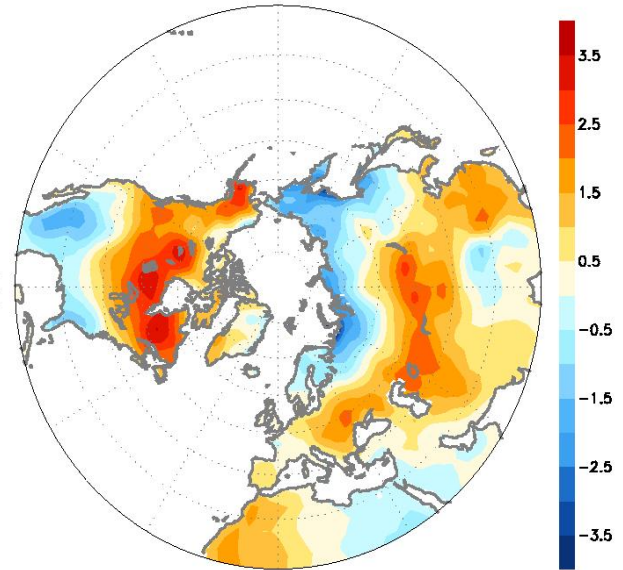
Days 1-60 following
stratospheric anomalies



QBO easterly-westerly



ENSO (warm-cold)



Day 1-60 after
Stratospheric
Anomalies

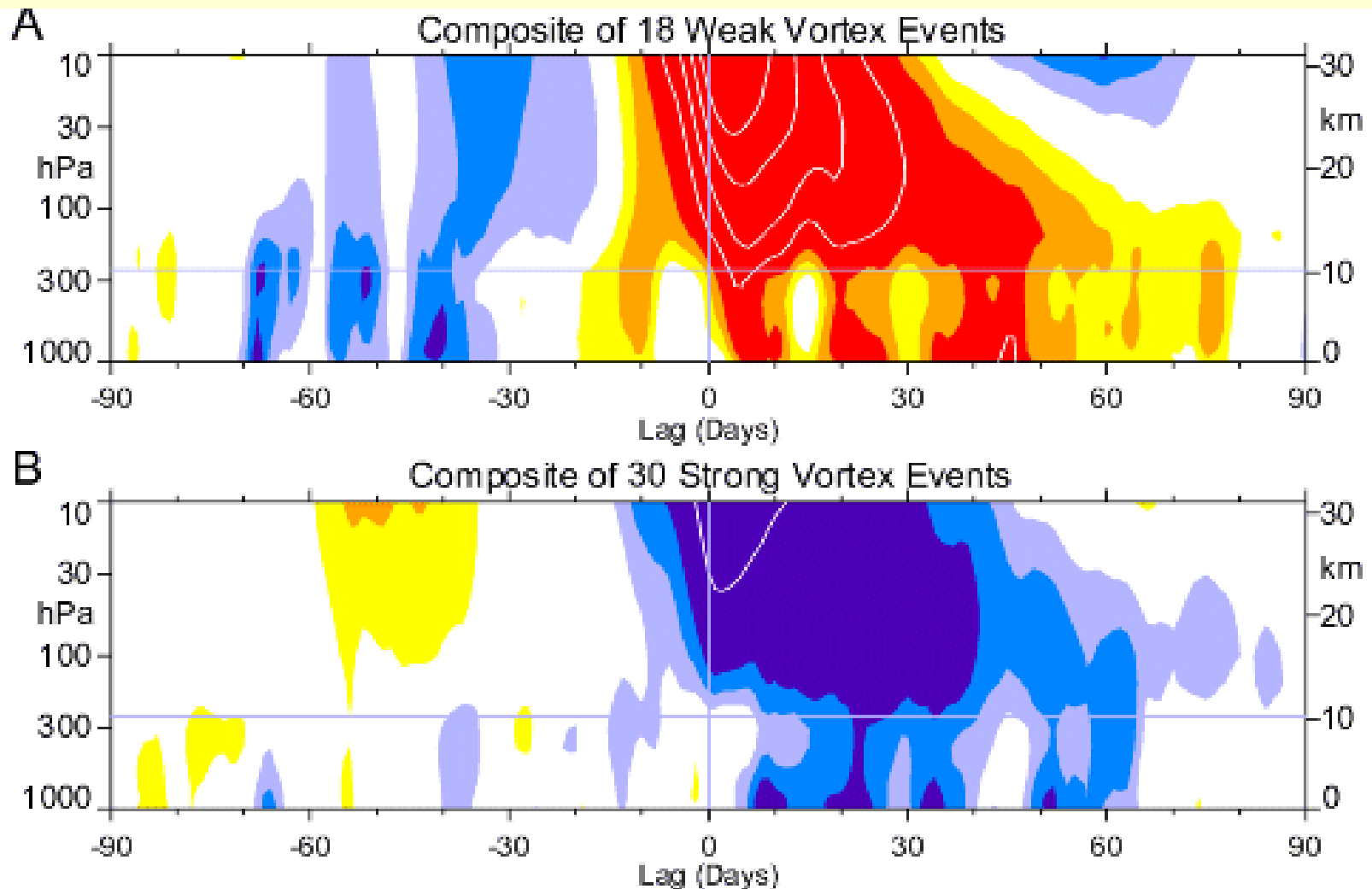
Jan. only
17 Easterly versus
17 Westerly

ENSO

$T(\text{negative NAM}) - T(\text{positive NAM})$
 $\text{weaker_vortex} - \text{stronger_vortex}$
28 cases versus 31 cases

*Thompson, Baldwin, and
Wallace (JC, 2002)*

Downward Propagation



- Downward propagation of geopotential height anomalies of both signs
- Larger anomalies (both signs) tend to reach the surface.
- Momentum and geopotential height anomalies are positively correlated.

(Baldwin and Dunkerton, 2001)

AO and Cold air surges

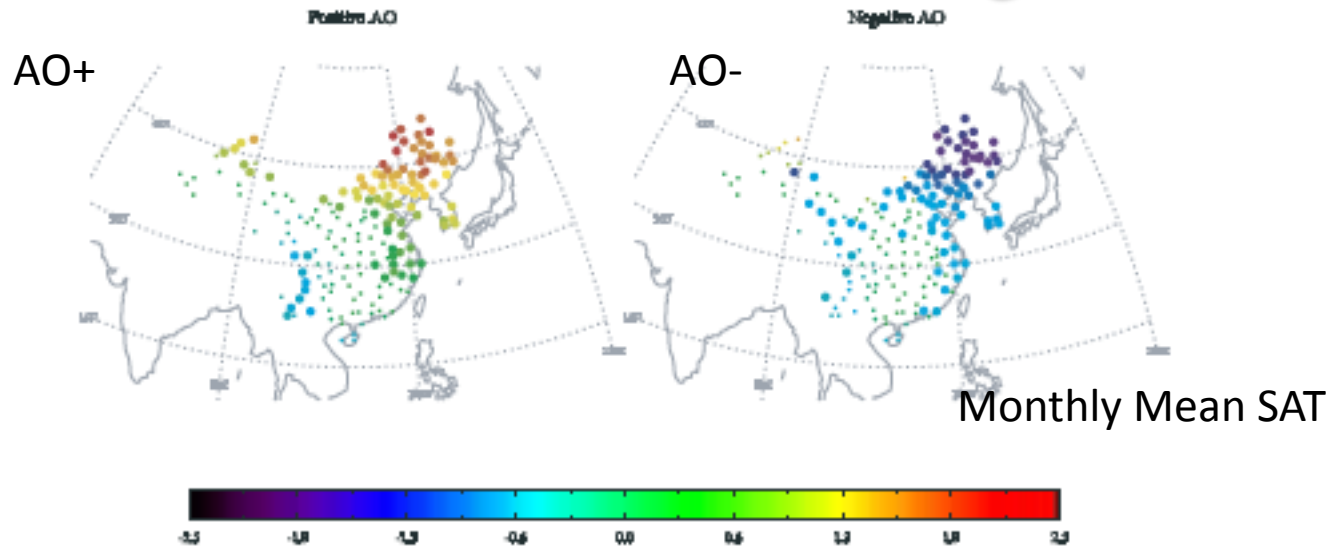
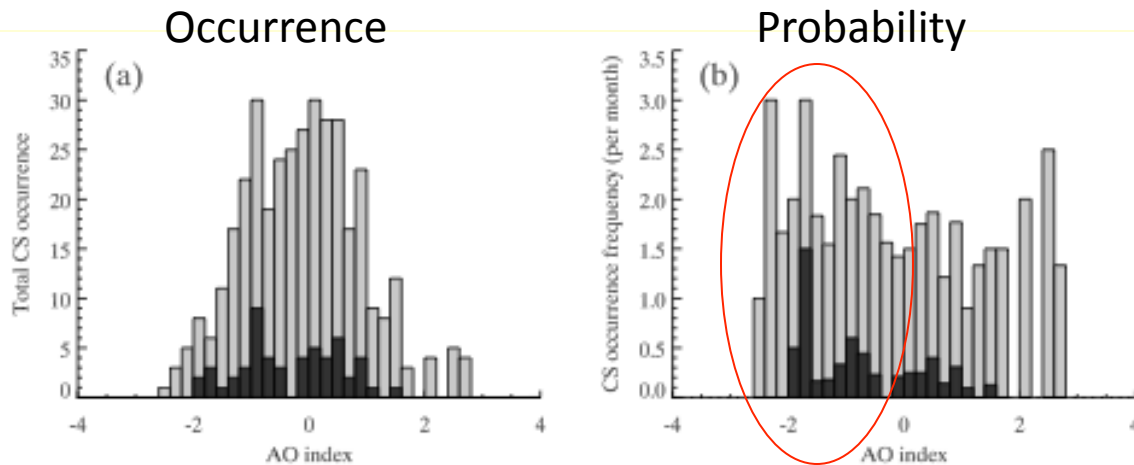


Figure 1. Composite monthly mean SAT anomaly (°C) based on AO index. Stations where the composite anomaly is statistically significant over the 90% significance level are denoted as large circle.



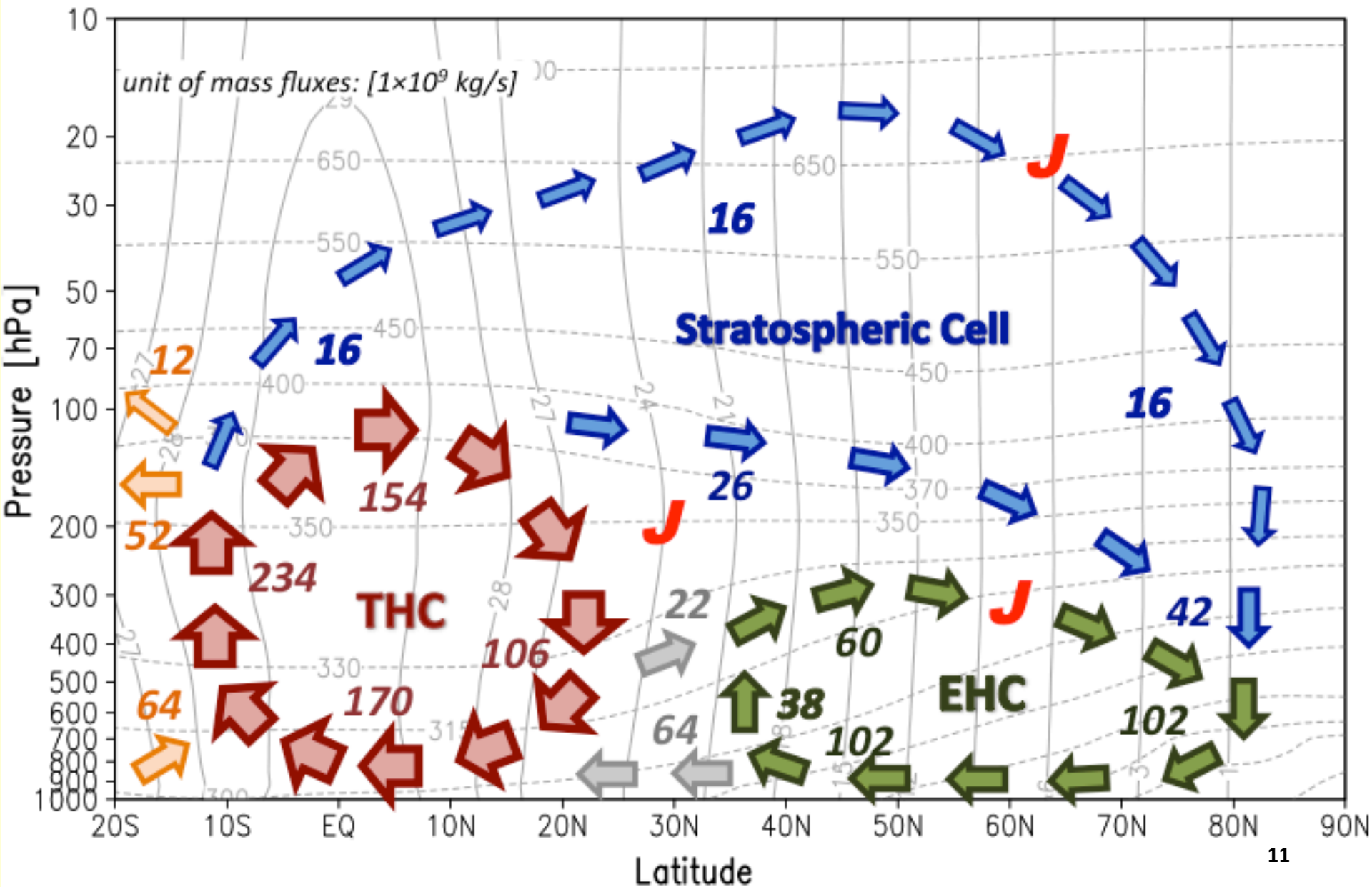
Monthly AO
but individual
cold air surge
events

Figure 2. Histogram of cold surge (a) occurrences and (b) frequency (total number of cold surge occurrences is divided by the total number of AO months) based on monthly AO index. Light and dark bars indicate normal and strong cold surges, respectively.

Jeong and Ho (2005, GRL)

Meridional mass circulation indices and cold air outbreaks

Mean meridional mass circulation in winter hemisphere (Cai and Shin 2014)



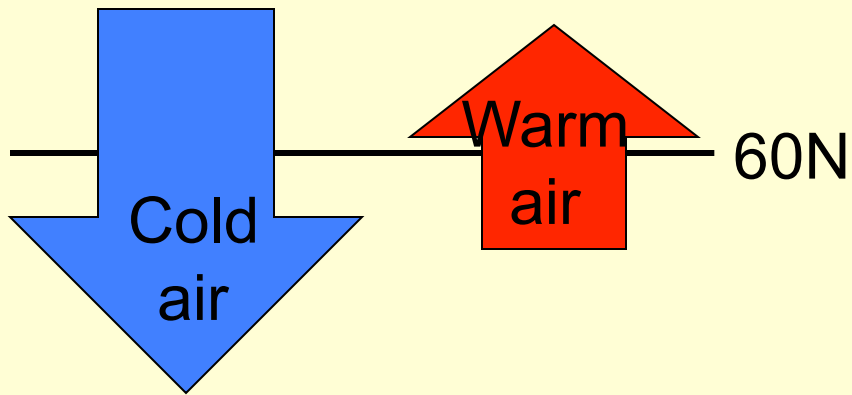
Vertical and meridional couplings by baroclinically amplifying (westward tilting) waves (Johnson 1989)

- A net poleward (adiabatic) transport of warm air mass aloft and a net equatorward (adiabatic) transport of cold air mass transport below.
- Stronger poleward air mass transport in the warm air branch aloft is coupled with stronger air mass transport in the cold air branch near the surface and vice versa.

Mass circulation variability and cold air outbreaks in the mid-latitudes

Weaker Meridional Mass
Circulation near surface

90N

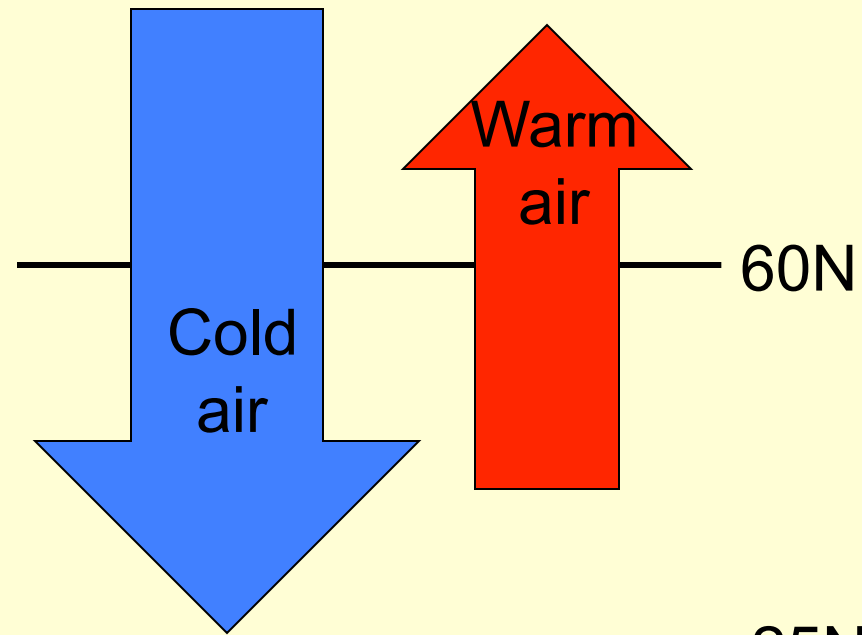


60N

25N

Stronger Meridional Mass
Circulation near surface

90N



60N

25N

Less cold air outbreaks in
mid-latitudes

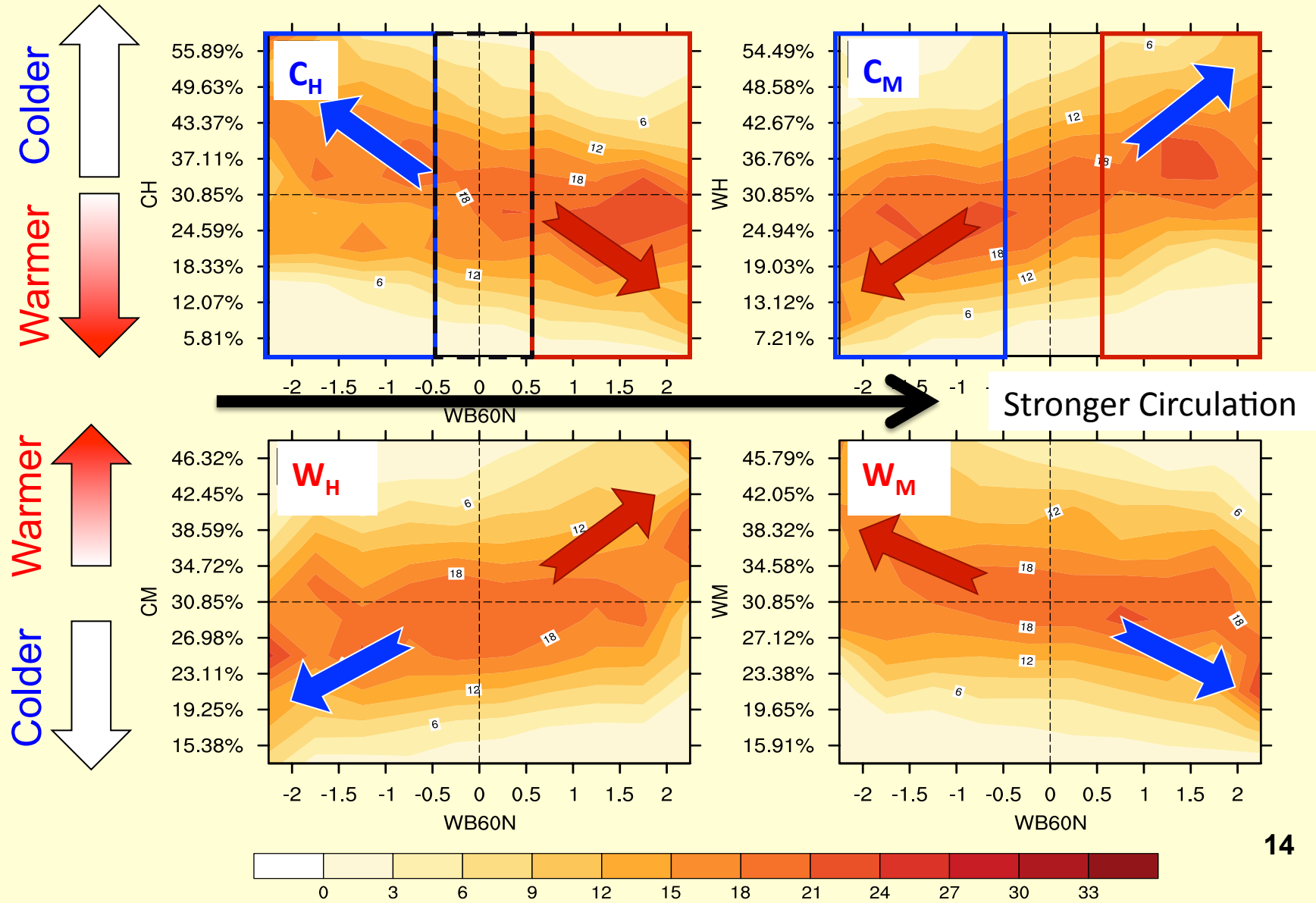
Coldness in high latitudes

More cold air outbreaks in
mid-latitudes

Warmness in high latitudes¹³

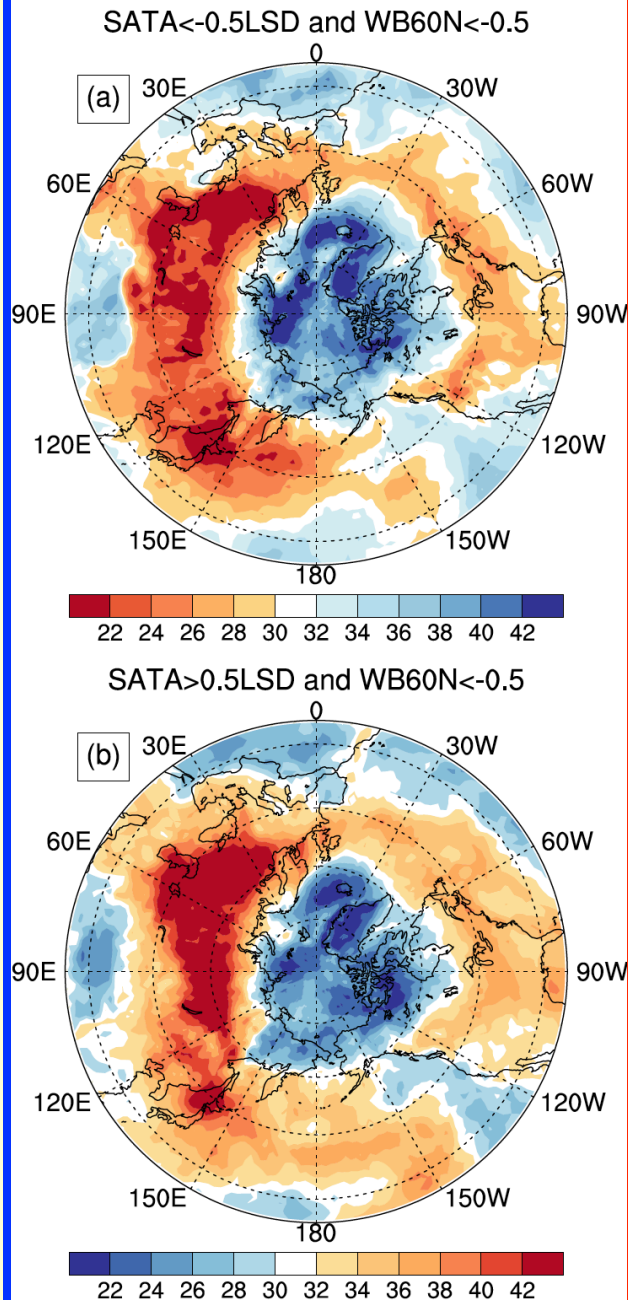
Relation of WB60N with Temperature Indices

Shift of PDFs of temperature indices in **charging**/**discharging** period of WB60N

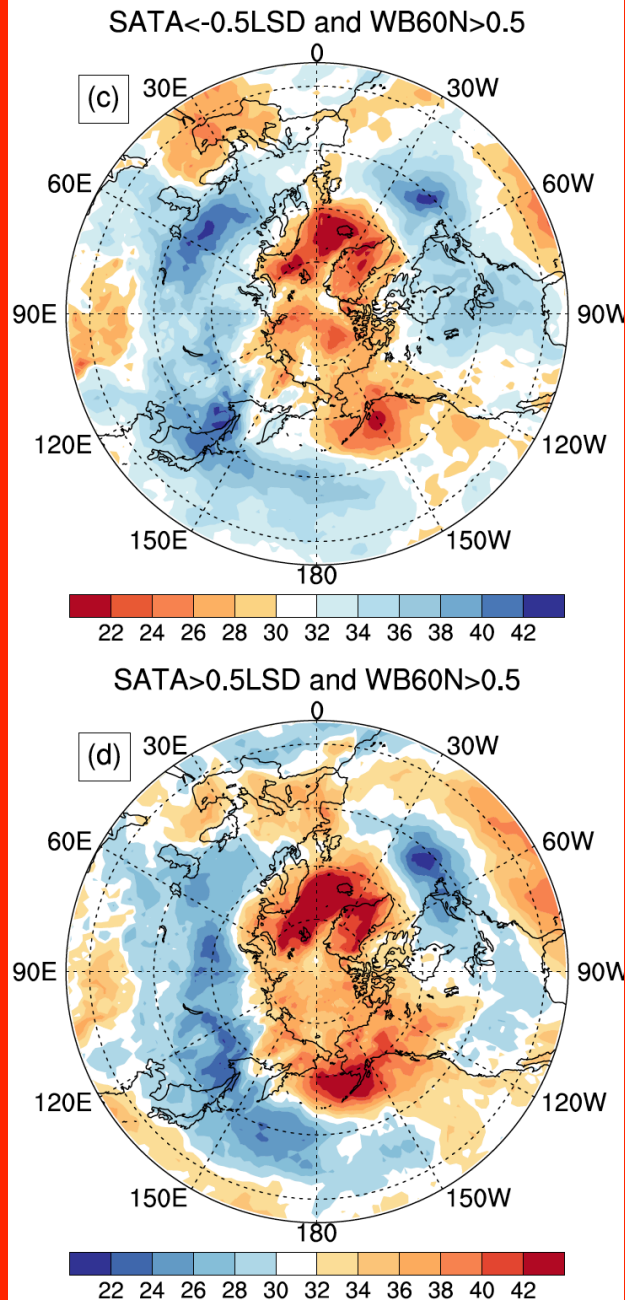


Maps of Probability of $T > 0.5\text{LSD}$ or $T < -0.5\text{LSD}$

Weak Circulation



Strong Circulation



**Occurrence
Prob of
 $T < -0.5\text{LSD}$**

**Occurrence
Prob of
 $T > 0.5\text{LSD}$**

Key Findings of Yu et al. (2015)

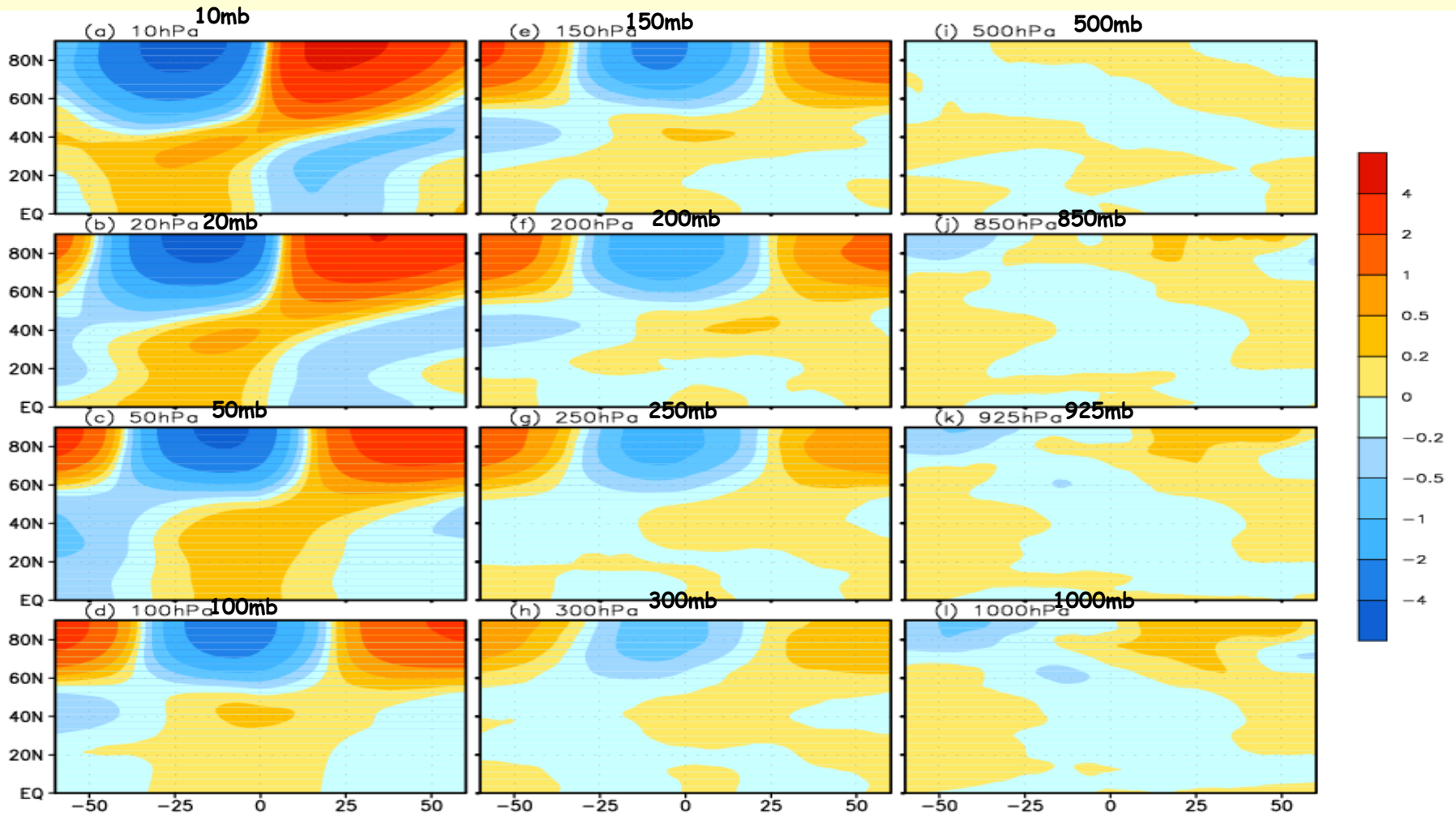
- Variability of mass flux warm air branch is **synchronized** with that of cold air branch.
- **Lack of warm air into polar region** is accompanied by weaker equatorward advancement of cold air near the surface. As a result, the cold air mass is largely imprisoned within polar circle, responsible for general **warmness in mid-latitudes** and **below climatology temperature in high latitudes**.
- **Stronger warm air into polar stratosphere** is accompanied by stronger equatorward advancement of cold air near the surface, resulting in massive **cold air outbreaks in mid-latitudes** and **warmth in high latitudes**.
- Associated with a stronger mass circulation event are warm over Arctic and cold over the two major continents or one of the two continents is cold whereas the other is warm.

Meridional propagation of thermal anomalies

Upper layers
totally in the ST

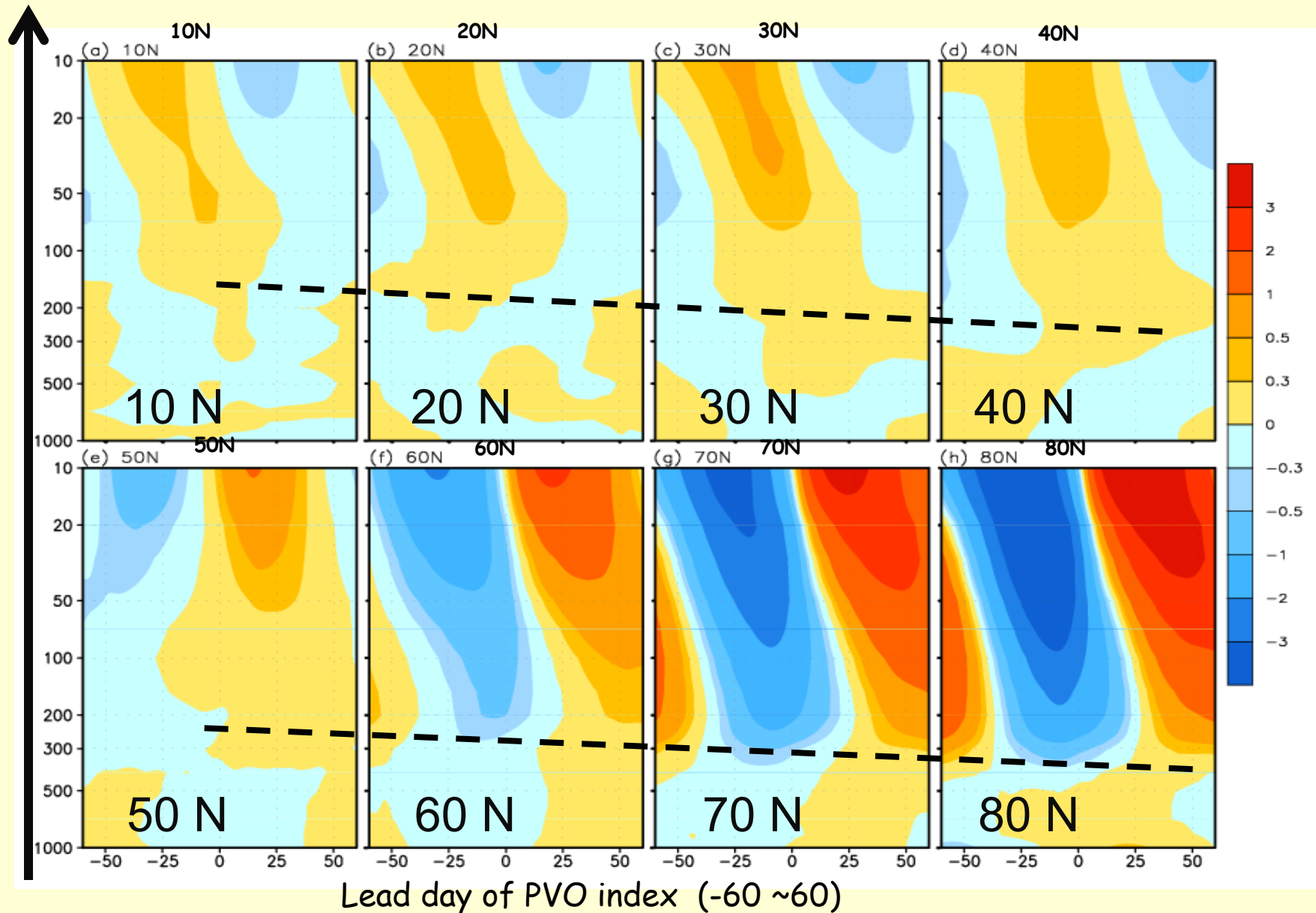
Middle layers across
the Tropopause

Troposphere

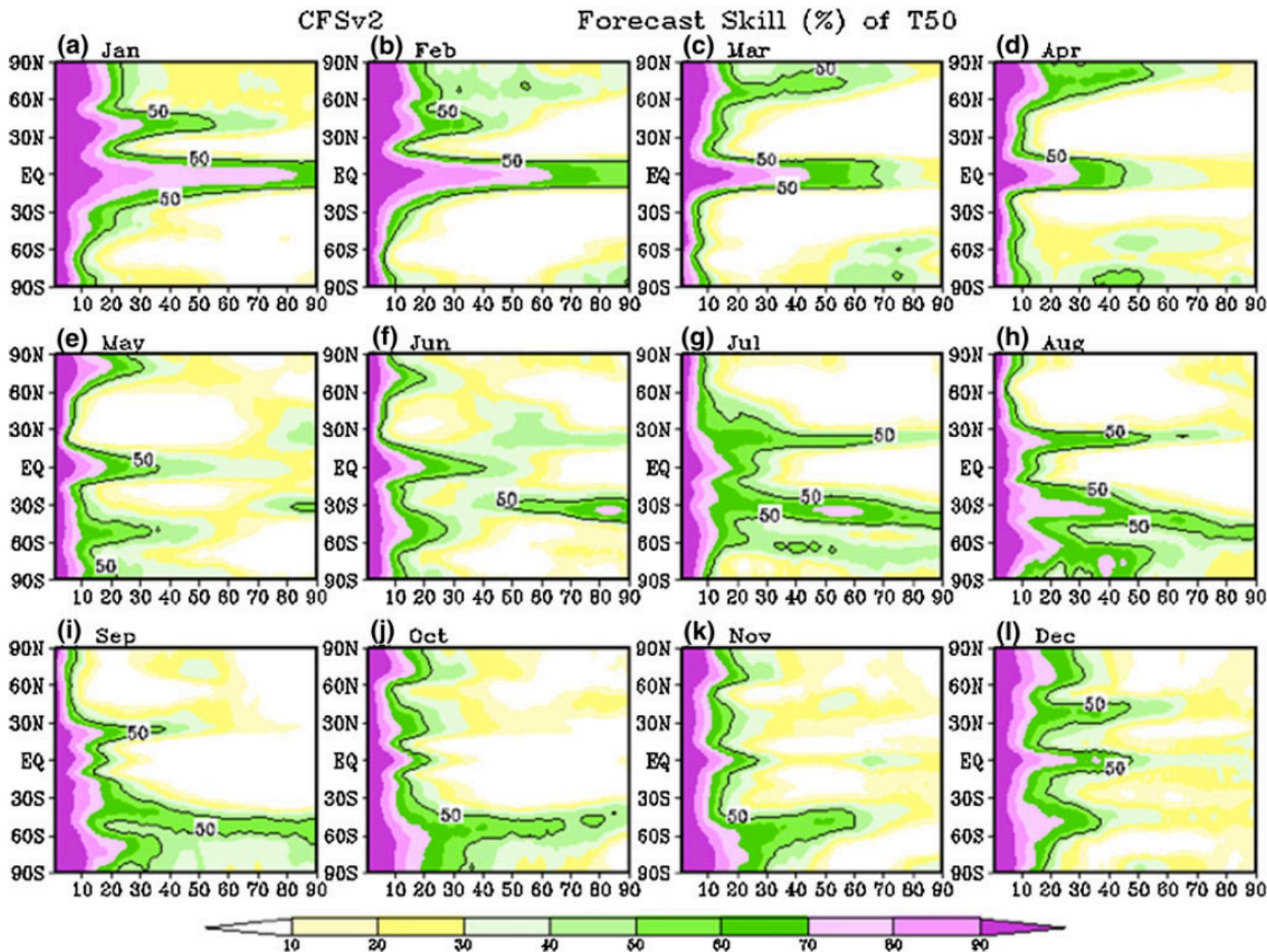


Lead day of PVO index (-60 ~60)

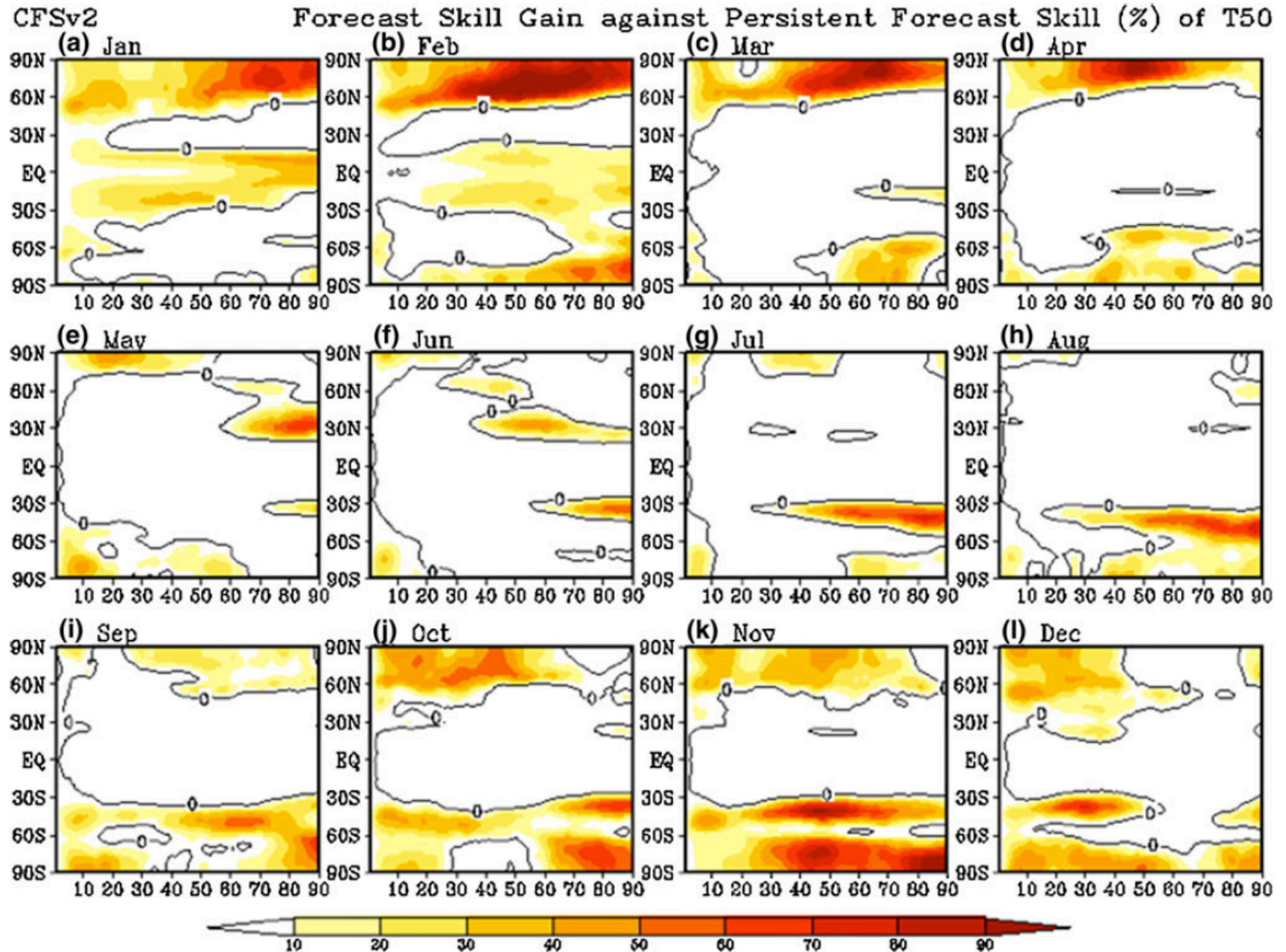
Downward Propagation of thermal anomalies



CFSv2 skill for zonal mean of T50 anomalies



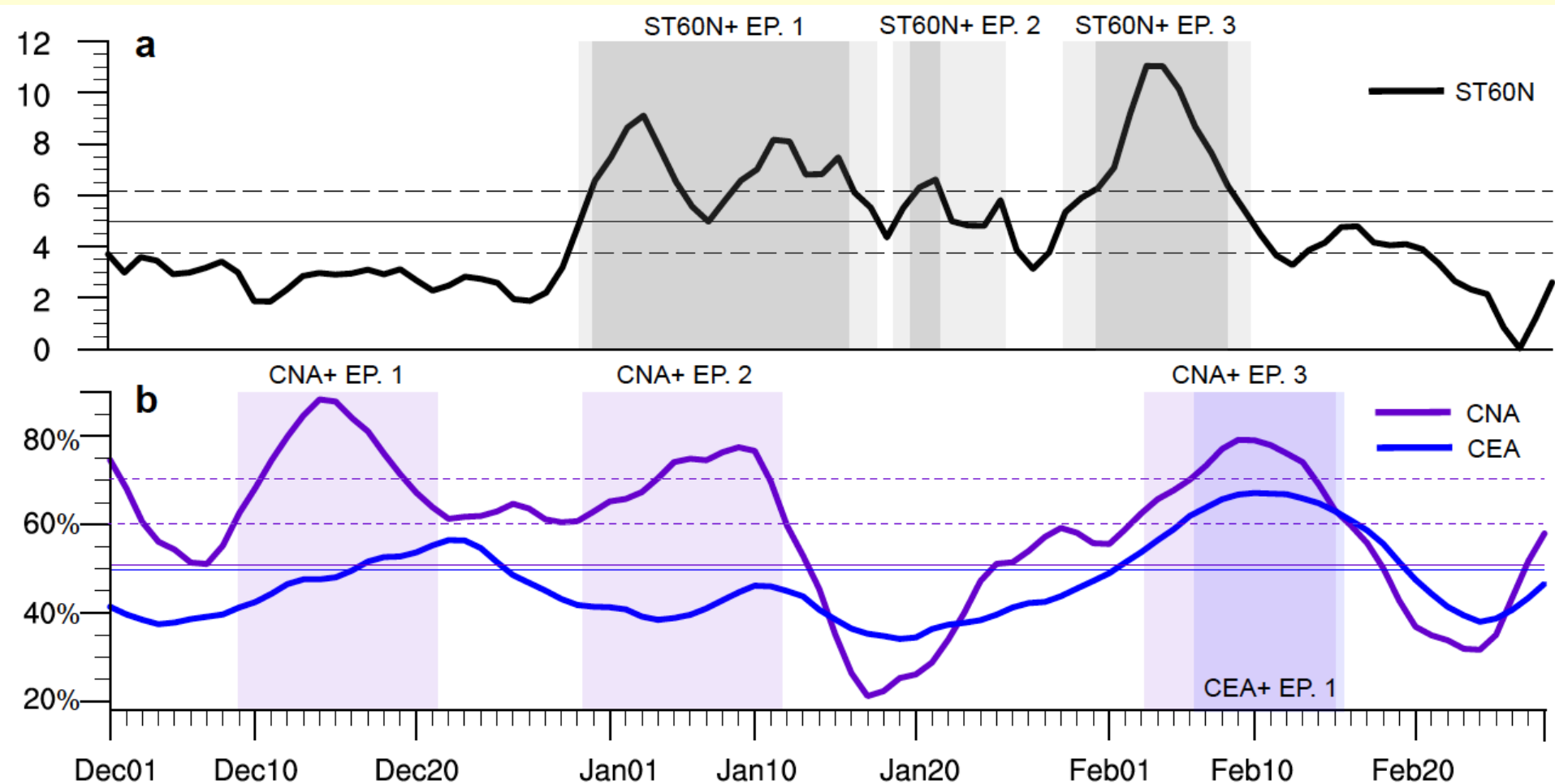
Gain of CFSv2 over persistence forecasts



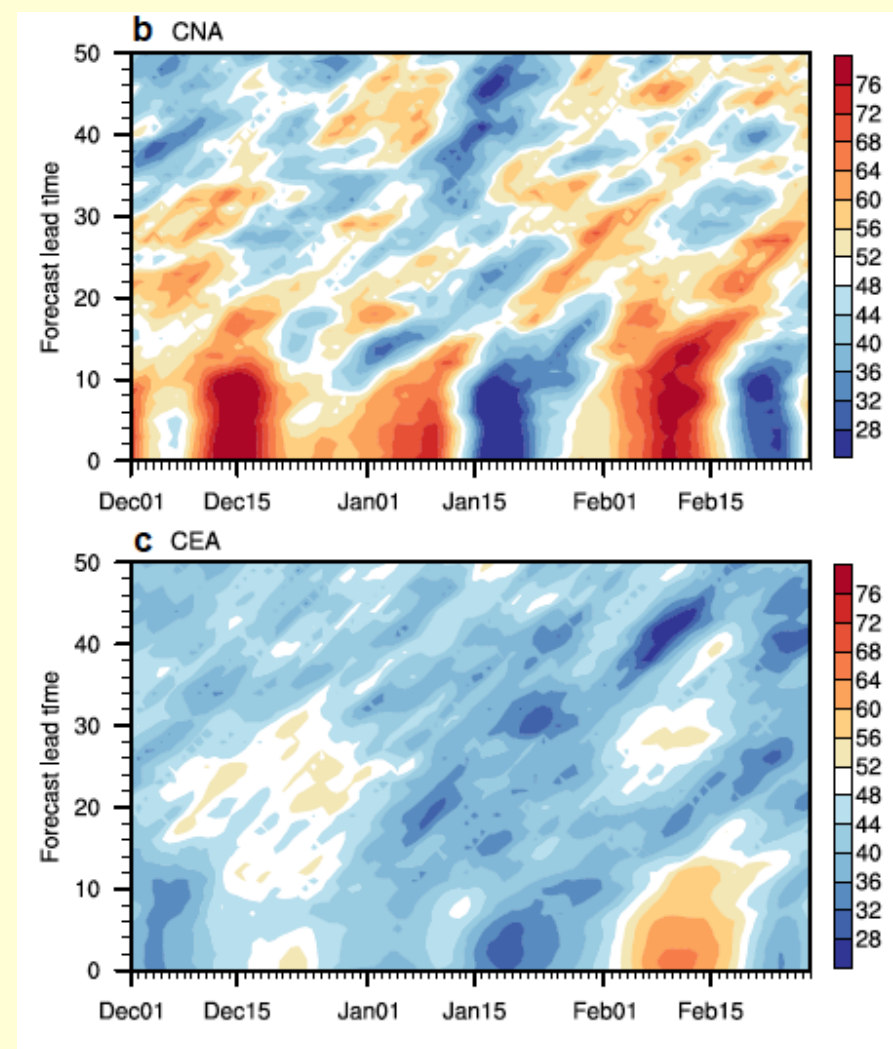
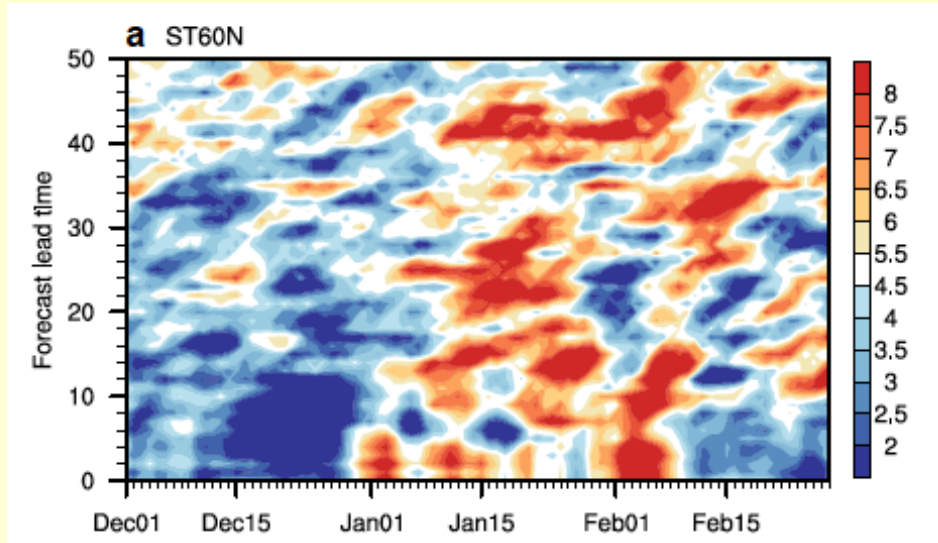
Key Findings of Zhang et al. (2013)

- The NCEP CFSv2 still has a remarkable skill in predicting mid-winter polar stratosphere warming events and the timing of the yearly final polar stratosphere warming in both hemispheres 3-4 weeks in advance. We also prove that the CFSv2 has a high prediction skill for winter polar stratosphere both in an absolute sense and in terms of gain over the persistence.
- The remarkable skill comes from the signal of systematic poleward propagation of thermal anomalies in the stratosphere associated with the global mass circulation variability (intensity/time scale).
- As long as the westward tilting of planetary waves in the stratosphere and their overall amplitude can be captured, the CFSv2 forecasts would still be very skillful in predicting zonal mean anomalies even though it cannot do so for the exact locations of planetary waves and their spatial scales.

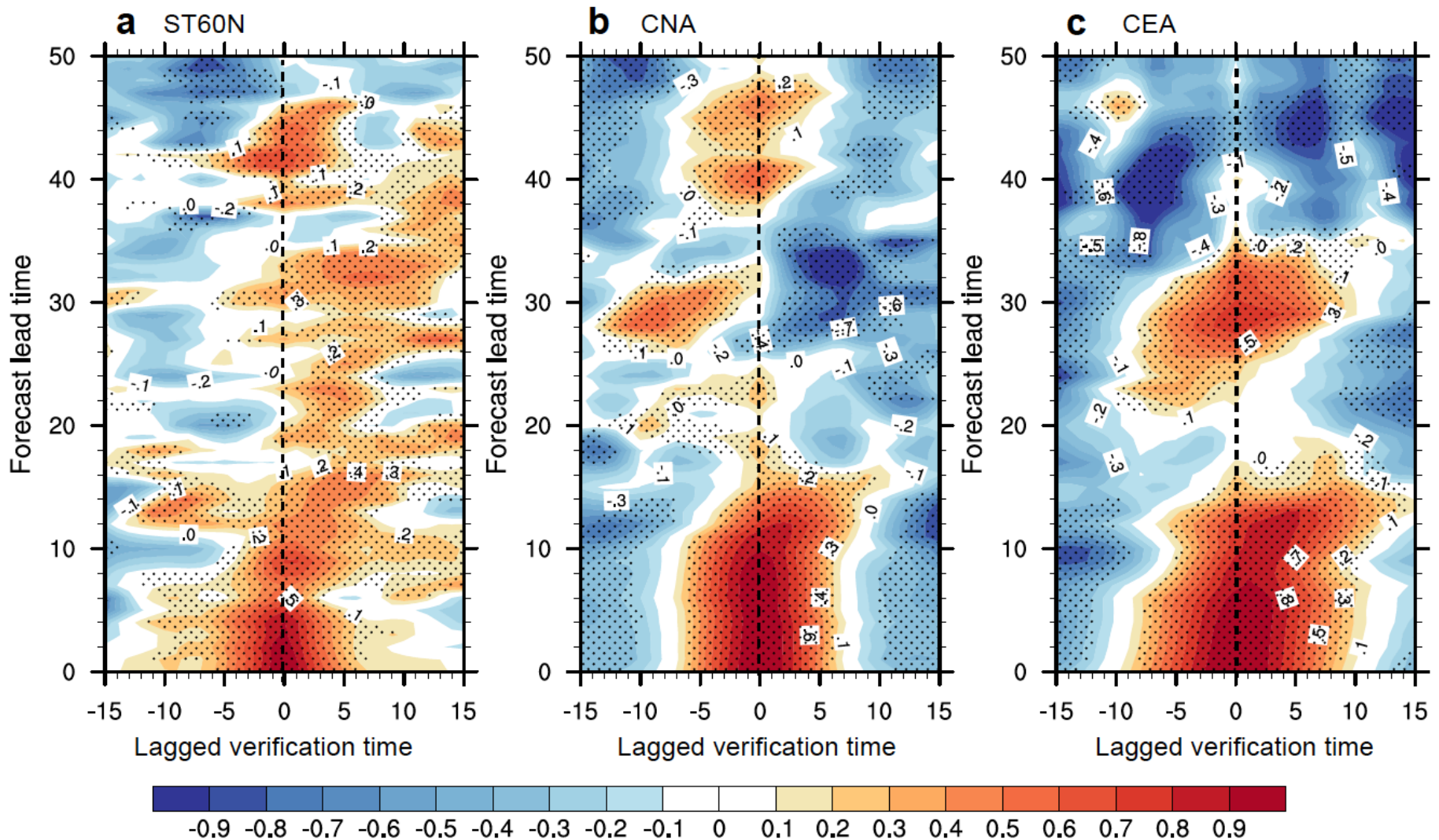
Relationship between ST60N and Cold Temp. Area Indices in 2013-14 winter



CFS Forecasts for ST60N and Cold Temp. Area Indices in the winter of 2013-14



Correlation Skill of CFSv2 Forecast for ST60N and Cold Temp. Area Indices in the winter of 2013-14



Lab of Experimental Forecast for Cold Air Outbreaks (in real time)

(www.amccao.com)

What we do: We are making sub-seasonal forecasts for time periods of high probability of cold air outbreaks in Eurasia and North America 30-40 days in advance. We issue such forecasts on a weekly basis and this website is updated around Thursday each week.

Hybrid procedures of sub-seasonal forecasts for cold air outbreaks (lead time 20-40 days)

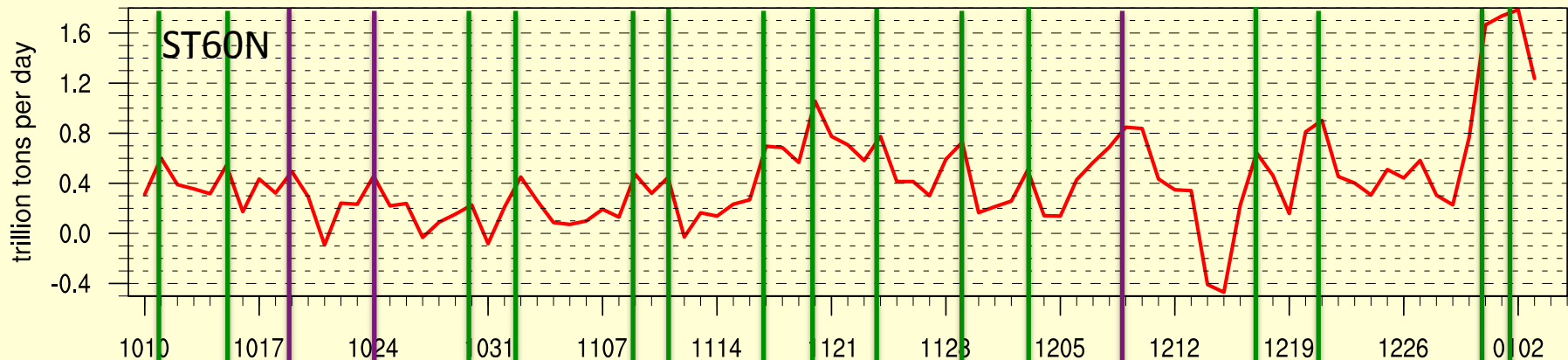
- Prognostic component: Dynamical predictions for mass circulation intensity into polar stratosphere derived from operational CFSv2 forecasts in real time plus forecasters' knowledge.
- Diagnostic component: Statistical “instantaneous” relationships between stratospheric circulation strength and surface temperature anomalies (downscaling).
- Products: Time Periods of strong mass circulation events and cold air outbreaks

Summary of forecasts in 2014-15 winter

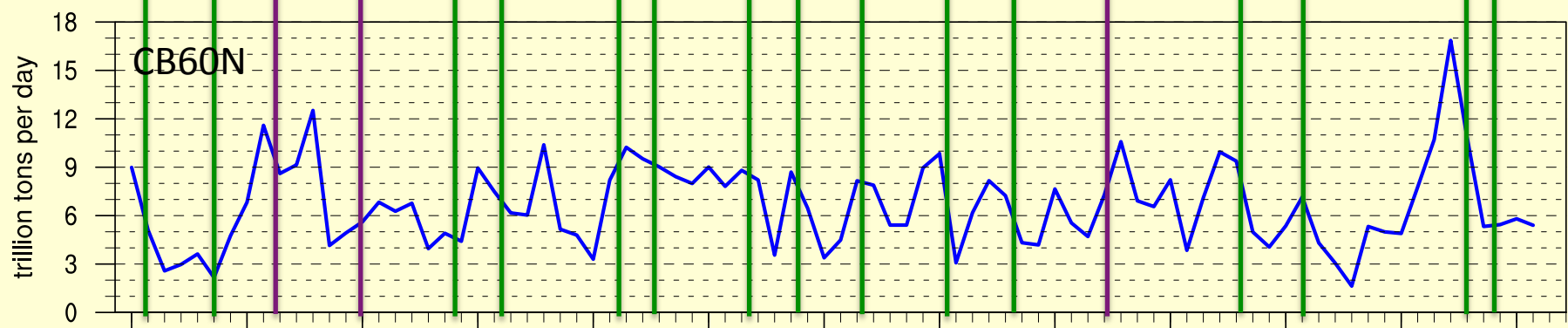
(www.amccao.com)

- Made 14 forecasts: no false alarm forecasts and 12 of them took place within a range of our forecasts (2 for events after March 12, 2015: **one issued on 02/12 to occur in 03/12-17** (three peaks on March 16, 18, and 23) **a major event** and the **other issued on 02/18 to occur in the last few days of March and first few days in April, a major event, revised on 03/12 to occur with a week around March 30**).
- Average lead time is 30+ days.
- All forecasted stratospheric events are associated with cold air breaks within few days of the peak times of stratospheric events except STRAT_F (01/16), covering a total of 31 round of cold air outbreaks.
- We only “missed” 8 rounds of cold air outbreaks which did NOT have strong stratospheric signals but only few days after the cold air outbreaks that we predicted.

Observed Stratosphere Mass Transport Into Polar Circle



Observed Total Cold Air Transport Out Of Polar Circle



STRAT_A

10/8-13 (9/29)
10/11 & 10/15,
10/19, & 10/24

STRAT_B

10/28-11/3(9/29)
10/30 & 11/01
Leadtime:
30+ days

STRAT_C

11/12-15 (10/6)
11/07-11 (10/21)
Leadtime:
30+ days

STRAT_C1

11/20-25 (10/6)
11/18-23 (11/6)
Leadtime:
44 days*

STRAT_D

12/03-07 (10/28)
11/29, 12/3,
& 12/9
Leadtime
30 days

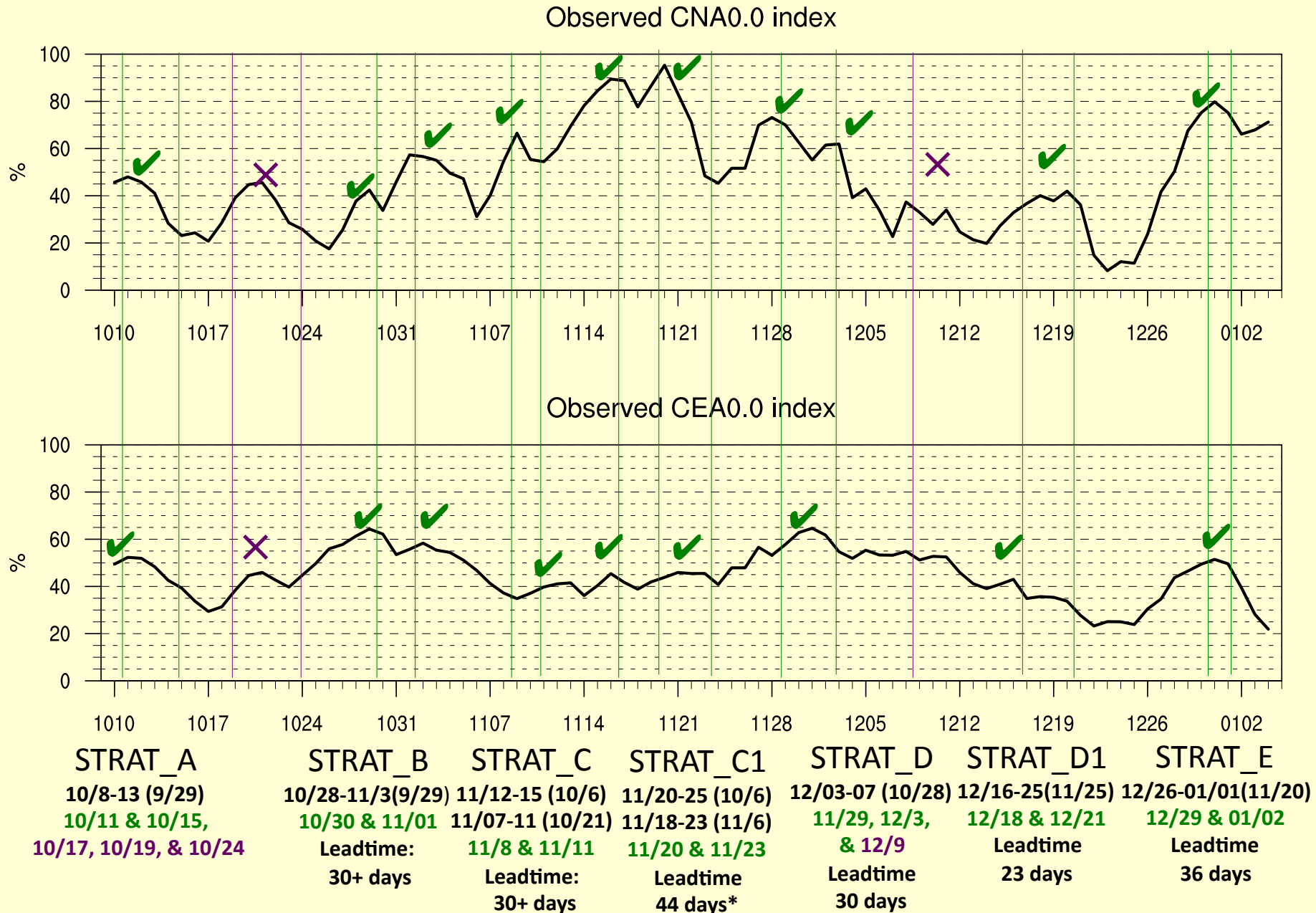
STRAT_D1

12/16-25(11/25)
12/17 & 12/21
Leadtime
23 days

STRAT_E

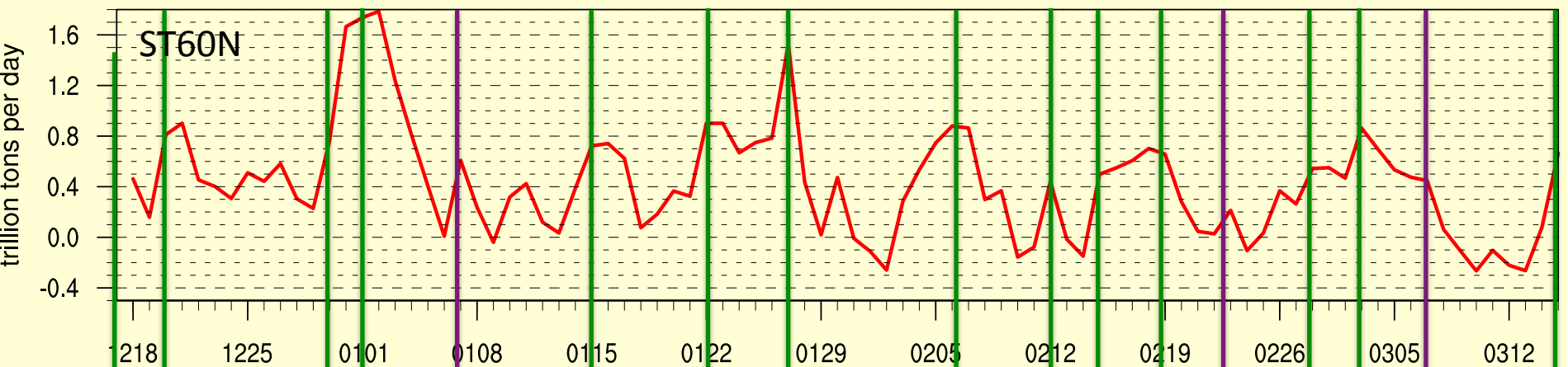
12/26-01/01(11/20)
12/29 & 01/02
Leadtime
36 days

Lines mark the peak times of the observed STRAT events; Black are the dates of STRAT events forecasted by us on the dates in the parenthesis; Dates in green are the actual peak days of those STRAT events forecasted by us and in purple are those not forecasted by us.

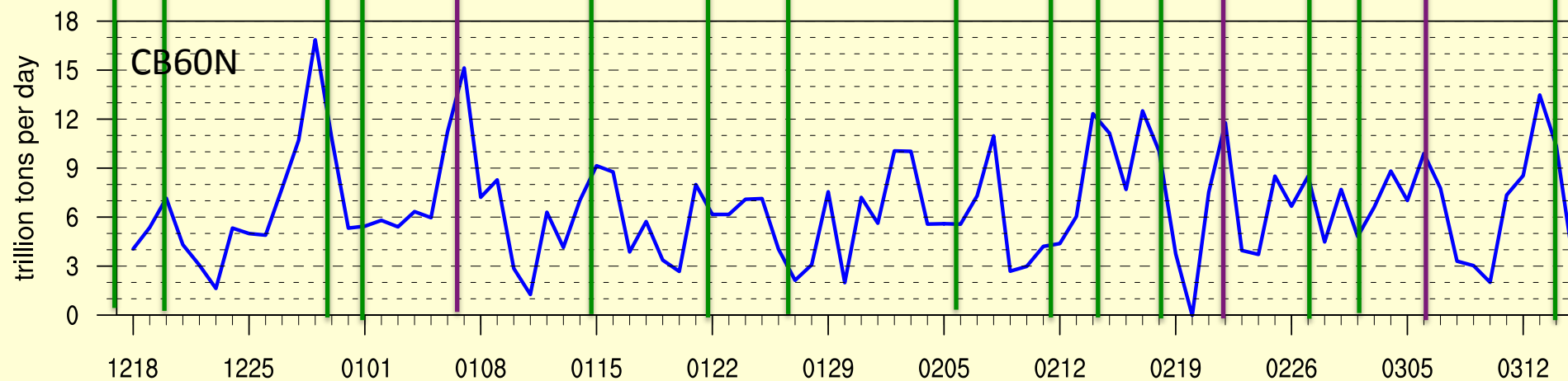


Green checks indicates cold air outbreaks are associated with STRAT events that are correctly forecasted by us and purple crosses indicate cold air outbreak events associated with STRAT events that are not forecasted by us.

Observed Stratosphere Mass Transport Into Polar Circle



Observed Total Cold Air Transport Out Of Polar Circle



STRAT_D1

12/16-25(11/25)

12/17 & 12/21

Leadtime

23 days

STRAT_E

12/26-01/01(11/20)

12/31 & 01/02

Leadtime

36 days

STRAT_G1

01/24-01/27 (12/17)

01/22 & 01/27 Leadtime

35 days

STRAT_H

02/13-02/18 (01/10)

02/12, 02/15, & 02/19 Leadtime

35+ days

STRAT_J

03/12-03/17 (02/12)

3/15 *** Leadtime

30+ days

STRAT_F

01/15-01/20 (12/05)

01/16 Leadtime

41 days

STRAT_G2

02/02-02/06 (12/17)

02/06 Leadtime

50 days

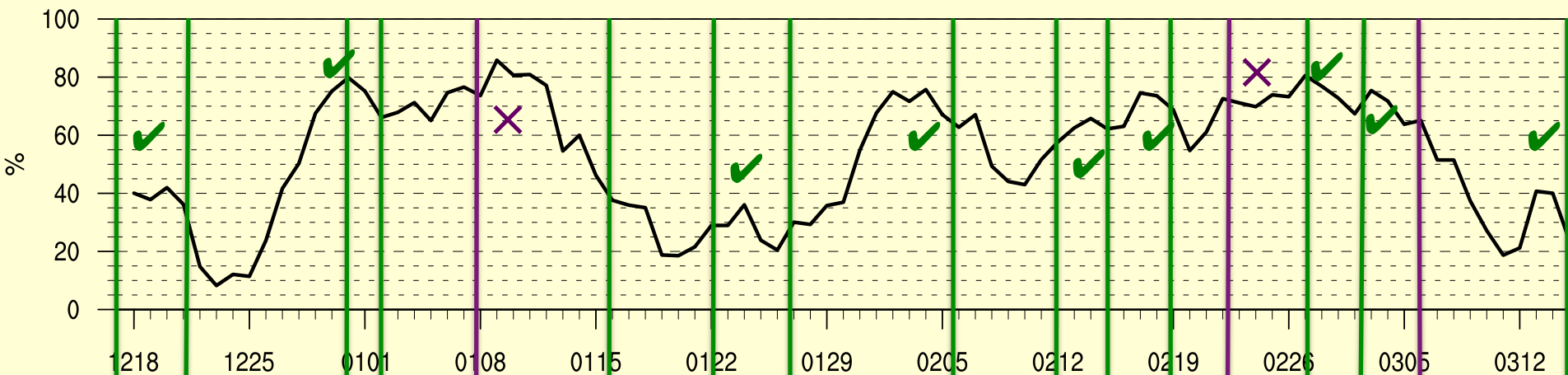
STRAT_I

02/27-03/04 (01/29)

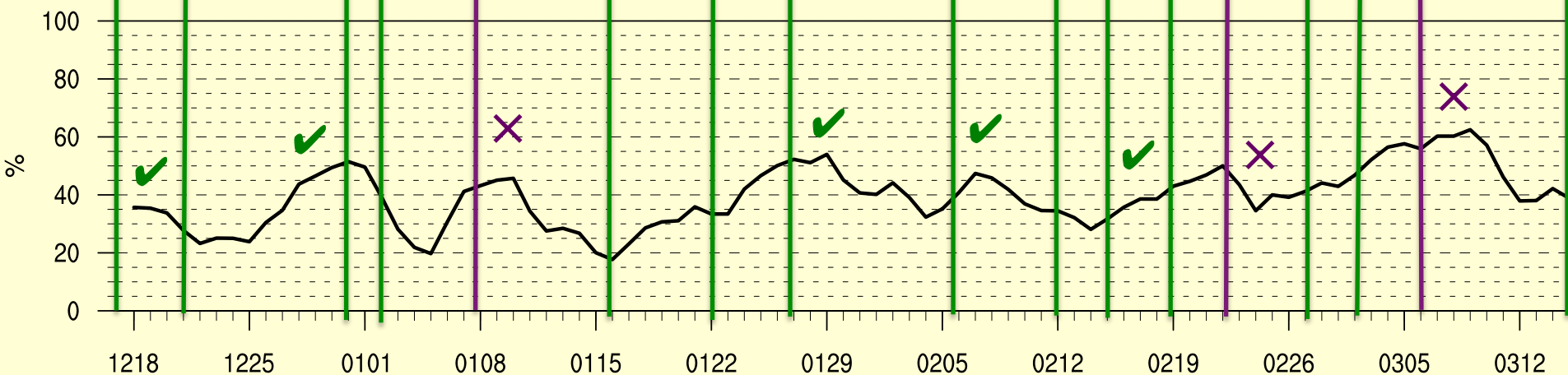
02/28 & 3/3 Leadtime

30+ days

Observed CNA0.0 index



Observed CEA0.0 index



STRAT_D1

12/16-25(11/25)

12/17 & 12/21

Leadtime
23 days

STRAT_E

12/26-01/01(11/20)

12/31 & 01/02

Leadtime
36 days

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02/12, 02/15, & 02/19 Leadtime

35+ days

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02/06 Leadtime

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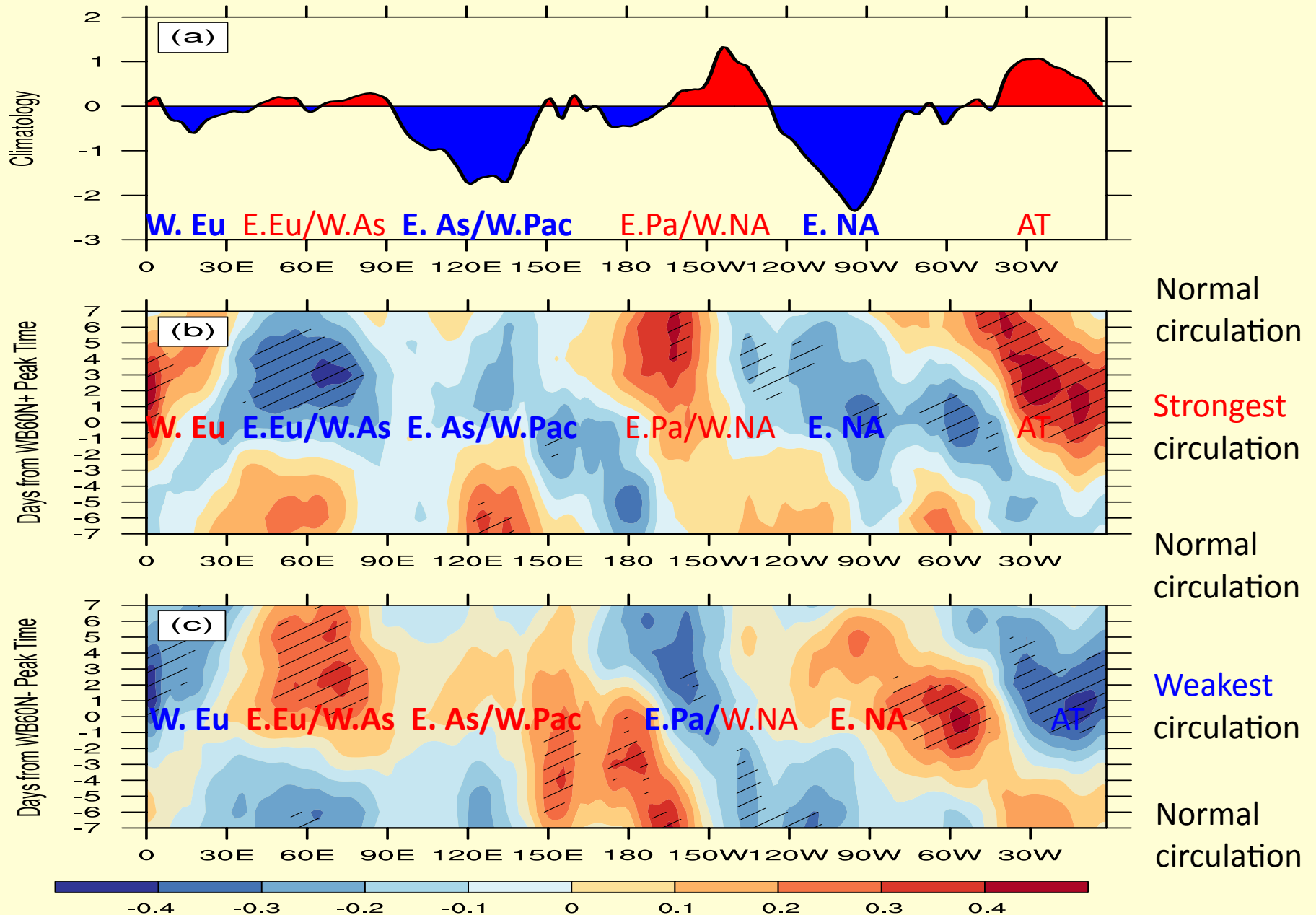
STRAT_I

02/27-03/04 (01/29)

02/28 & 3/3 Leadtime

30+ days

Preferred routes for cold air outbreaks



Conclusions

- There exists an intrinsic connection between the amount of air mass transported into the polar stratosphere and the probability of the occurrence of massive, continental-scale cold air outbreaks in the Northern Hemisphere.
- Numerical weather prediction models such as the NOAA CFSv2 is capable of predicting the air mass transported into the polar stratosphere with a good skill at a lead time longer than a month, although it cannot do so for tropospheric circulations.
- The combination of both factors leads to the creation of a hybrid (dynamical + statistical) paradigm that allows us, for the first time, to predict occurrences of massive cold air outbreaks one month in advance.